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RESEARCH ARTICLE

# Nano-Polymer Encapsulated Biofertilizers for Controlled Nutrient Release in Soil

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**Abstract:** The integration of nanotechnology with biofertilization offers a transformative solution for improving soil fertility and nutrient efficiency. This study explores the development and application of nano-polymer encapsulated biofertilizers designed for controlled nutrient release in soil. Conventional biofertilizers, while eco-friendly, often suffer from rapid nutrient loss, poor microbial survival, and inconsistent field performance. To address these limitations, biopolymers such as chitosan, alginate, and polyvinyl alcohol (PVA) were used as encapsulating matrices to form nanoscale carriers for microbial and nutrient cores. The encapsulation ensured gradual degradation and sustained nutrient availability, synchronized with crop demand. Laboratory incubation and pot trials revealed that encapsulated formulations significantly improved nitrogen and phosphorus use efficiency while maintaining microbial viability over 60 days. Compared to non-encapsulated biofertilizers, the nano-formulations reduced nutrient leaching by 35–40% and enhanced plant biomass and soil enzyme activity. These results demonstrate that nano-polymer encapsulated biofertilizers can revolutionize sustainable agriculture by minimizing input losses and enhancing soil–plant–microbe interactions. The study underscores their potential role in precision nutrient management systems and paves the way for large-scale implementation under varied agro-climatic conditions.

**Keywords:** Nano-polymer encapsulation; Biofertilizers; Controlled nutrient release; Chitosan nanoparticles; Soil fertility; Sustainable agriculture; Nutrient use efficiency; Microbial viability.

## INTRODUCTION

The increasing demand for food production to meet the needs of a growing global population has intensified the use of chemical fertilizers, resulting in significant ecological and agronomic challenges. Excessive and unregulated application of synthetic fertilizers has caused nutrient leaching, soil degradation, and contamination of groundwater systems, leading to long-term declines in soil fertility and environmental sustainability. Conventional fertilizers release nutrients rapidly, often exceeding the plant's uptake capacity, thereby reducing nutrient use efficiency (NUE) and increasing the risk of eutrophication in nearby aquatic systems. In this context, **biofertilizers** have emerged as an eco-friendly alternative, utilizing living microorganisms such as *Rhizobium*, *Azotobacter*, *Azospirillum*, and *Phosphate Solubilizing Bacteria* to enhance nutrient availability through biological nitrogen fixation and phosphorus solubilization. However, despite their proven benefits, biofertilizers often exhibit poor field performance due to low microbial survival, rapid desiccation, and uncontrolled nutrient release in diverse soil conditions. These shortcomings limit their efficiency and scalability in modern agricultural practices. The advent of nanotechnology has created new pathways to overcome these limitations through the **nano-encapsulation of biofertilizers using biodegradable polymers**, enabling precise control of nutrient release, protection of microbial activity, and improved soil–plant interaction. The use of polymeric nanocarriers has become a promising innovation that bridges biotechnology and materials science, aiming to increase the efficiency of nutrient delivery while maintaining ecological safety and sustainability.

Nano-polymer encapsulation technology involves coating or embedding biofertilizer formulations within nanoscale polymer matrices that control the diffusion of nutrients and microbial metabolites into the soil environment. Polymers such as **chitosan**, **alginate**, **starch**, and **polyvinyl alcohol (PVA)** are often used due to their biocompatibility, non-toxicity, and biodegradability. These polymers can form stable nanocapsules that gradually degrade under soil conditions, ensuring sustained release of nutrients over time. Such controlled-release systems offer multiple benefits: they prevent nutrient leaching, enhance microbial survival by protecting them from harsh environmental stresses, and synchronize nutrient availability with crop demand. Furthermore, nano-encapsulated biofertilizers improve soil enzymatic activity, increase organic matter content, and stimulate root colonization by beneficial microbes. Recent research has demonstrated that nano-carriers not only enhance the efficiency of nitrogen and phosphorus utilization but also reduce the total fertilizer requirement by up to 30–40% compared to conventional formulations. In addition, nanopolymers can be engineered to respond to environmental cues such as pH, temperature, or moisture, offering dynamic control over nutrient release patterns. This innovative approach directly aligns with the principles of **sustainable and precision agriculture**, reducing the ecological footprint of crop production. Despite these promising outcomes, large-scale field validation, biosafety assessment, and cost-effective production remain critical areas of ongoing research. Therefore, this paper focuses on exploring the design, synthesis, and functional performance of nano-polymer encapsulated biofertilizers for controlled nutrient release in soil, highlighting their role as a transformative technology for achieving efficient, eco-friendly, and sustainable nutrient management in agriculture.

## II. RELEATED WORKS

The intersection of nanotechnology and biofertilizer research has produced a rapidly expanding literature focused on improving nutrient use efficiency and protecting beneficial microbial inoculants. Early experimental work established the feasibility of encapsulating nutrients and microbes within biodegradable polymer matrices such as chitosan, alginate, starch, and polyvinyl alcohol, demonstrating improved survival of inoculants under desiccation and UV stress [1][2]. Laboratory-scale studies reported enhanced nitrogen fixation and phosphate solubilization when microbes were delivered in protective matrices compared with unprotected inocula [3][4]. Kinetic experiments on nutrient diffusion from polymeric matrices confirmed that matrix composition and crosslinking density strongly regulate release rates, and models based on Fickian diffusion and Higuchi kinetics were widely applied to fit observed release profiles [5][6]. Comparative analyses further showed that natural polysaccharide carriers tend to be more biocompatible and biodegradable but may offer less mechanical robustness than synthetic polymers, leading researchers to explore blends and composite nanocarriers to balance stability and degradability [7][8]. Work on stimulus-responsive carriers that alter release in response to soil pH, moisture, or enzymatic activity has begun to translate theoretical promise into practical designs, with several groups reporting moisture-triggered swelling and release behaviors that better synchronize nutrient availability with plant demand [9][10].

Field and pot-trial evidence supports the agronomic benefits of nano-encapsulated fertilizers and biofertilizers, although results vary with crop, soil, and climate. Multiple greenhouse and small-plot field experiments reported increased biomass, higher chlorophyll content, and improved yield under treatments with nanoparticle-enabled slow-release fertilizers compared with conventional broadcast fertilizers, often accompanied by reductions in leaching losses and nitrous oxide emissions [11][12]. Studies that combined nutrient nanocarriers with plant growth promoting rhizobacteria (PGPR) observed synergistic effects: the nanocarrier protected microbial viability while providing a steady nutrient supply that enhanced root colonization and plant uptake [3][13]. Economic assessments at small scales suggested potential cost savings through reduced application frequency and lower total nutrient inputs, though manufacturing cost remained a barrier to widespread adoption [14]. Several meta-analyses attempted to synthesize these disparate results and concluded that while average improvements in nutrient use efficiency and yield are positive, effect sizes are heterogeneous and strongly context dependent, highlighting the need for standardized protocols for formulation, application rate, and performance metrics [15].

Despite promising outcomes, important gaps and risks remain the focus of recent reviews and experimental critiques. Biosafety and ecotoxicological studies are limited in number and scope, leaving open questions about nanoparticle fate, transformation, and indirect effects on non-target soil biota and food chains [7][11]. Long-term field trials that account for seasonal variability, crop rotations, and cumulative soil loading are scarce, constraining confidence in claims of sustainability over agricultural timescales [12][14]. Regulatory frameworks have not kept pace with technological advances; consensus is lacking on testing standards, permissible materials, and labeling for nano-enabled agroinputs [8][15]. Methodological issues also complicate interpretation: analytical techniques for quantifying nanocarrier residues in complex matrices are still evolving, and release kinetics measured in idealized laboratory media often fail to predict behavior in heterogeneous soils [5][9]. Addressing these limitations, recent work advocates integrated research programs that combine mechanistic laboratory studies, systematic small-plot field trials, rigorous ecotoxicology, and life cycle assessments to evaluate environmental trade-offs and economic viability [10][13]. Taken together, the literature establishes a clear technical foundation for nano-polymer encapsulation of biofertilizers and suggests substantial agronomic promise, while simultaneously underscoring the urgent need for coordinated research on safety, scalability, and standardization before large-scale deployment.

# MATERIAL AND METHODS

### 3.1 Research Design and Framework

This study adopts an **experimental and analytical research design** that integrates **nano-polymer synthesis, encapsulation of biofertilizers, soil incubation trials, and nutrient-release kinetics analysis**. The overall objective is to evaluate the controlled release behavior of nutrients from nano-polymer encapsulated biofertilizers and assess their agronomic and environmental performance. The methodology is designed to systematically link **formulation characteristics**, **release dynamics**, and **plant–soil responses**, ensuring scientific reproducibility and ecological relevance. The work follows a multi-phase approach including (a) preparation of polymeric nanocarriers, (b) encapsulation of microbial and nutrient cores, (c) laboratory incubation for nutrient-release profiling, and (d) soil-plant assays for bioefficacy assessment [16][17]. Each phase includes both qualitative and quantitative evaluation through **physicochemical characterization** and **statistical validation**.

### 3.2 Synthesis of Nano-Polymer Matrix

The polymeric nanocarriers were synthesized using **ionic gelation and emulsion polymerization techniques**, depending on the polymer type. Natural polymers such as **chitosan** and **sodium alginate** were selected for their biodegradability, while **polyvinyl alcohol (PVA)** was incorporated to improve structural stability and hydrophilicity. The **chitosan–alginate system** was optimized using calcium chloride as a cross-linker. The resulting nanoparticles were centrifuged, washed, and freeze-dried for encapsulation experiments. Particle size distribution was determined by **Dynamic Light Scattering (DLS)**, and surface morphology was observed under **Scanning Electron Microscopy (SEM)**, confirming spherical nanoparticles within the 50–200 nm range [18]. The **zeta potential** was measured to evaluate colloidal stability, maintaining values between +25 and +40 mV, indicative of good dispersion and surface charge stability.

**Table 1: Composition and Characteristics of Nano-Polymer Matrices**

| Formulation Code | Polymer Type | Crosslinker Used | Particle Size (nm) | Zeta Potential (mV) | Encapsulation Efficiency (%) |
|---|---|---|---|---|---|
| NP1 | Chitosan | Na-TPP (Tripolyphosphate) | 95 ± 10 | +32 | 78.4 ± 2.3 |
| NP2 | Alginate | $CaCl_2$ | 142 ± 12 | -28 | 82.6 ± 3.7 |
| NP3 | Chitosan–Alginate | $CaCl_2$ + Na-TPP | 115 ± 15 | +35 | 85.2 ± 2.9 |
| NP4 | PVA–Starch Blend | Glutaraldehyde | 165 ± 18 | -25 | 80.5 ± 3.1 |

Source: Experimentally developed based on standard encapsulation protocols [19].

### 3.3 Encapsulation of Biofertilizers

Selected microbial strains including *Rhizobium sp.*, *Azospirillum brasilense*, and *Bacillus megaterium* were cultured in nutrient broth under sterile conditions. A **coacervation technique** was used to encapsulate microbial cultures and nutrient cores (nitrogen and phosphorus compounds) within polymeric nanoparticles. The encapsulation process was optimized to achieve high microbial survival rates and uniform dispersion. The nano-polymer suspension was mixed with microbial broth, followed by gentle stirring at controlled pH (6.8–7.0) and temperature (25°C). The resulting nano-biofertilizer beads were separated, air-dried, and stored at 4°C until use. **Encapsulation efficiency** was calculated as the ratio of nutrient retained within the matrix to the total nutrient input, expressed in percentage terms. The encapsulated microbes retained >80% viability after 30 days of storage, indicating superior stability compared to non-encapsulated controls [20].

### 3.4 Controlled Nutrient Release Study

Controlled release kinetics were assessed using **soil incubation experiments** under laboratory conditions. Known quantities of encapsulated and non-encapsulated biofertilizers were placed in soil microcosms maintained at 60% field capacity. Samples were withdrawn at regular intervals (1, 3, 7, 14, 21, 30, and 45 days), and available nitrogen ($NH_4^+$–N and $NO_3^-$–N) and phosphorus (Olsen P) were analyzed spectrophotometrically. The release data were fitted to **Higuchi and Korsmeyer–Peppas models** to determine release constants and diffusion mechanisms [21].

### 3.5 Soil Incubation and Plant Growth Assay

Soil samples were collected from agricultural plots (0–15 cm depth), sterilized, and characterized for pH, texture, and organic matter. A **randomized block design (RBD)** was implemented for pot experiments with five treatments:
T1 – Control (No fertilizer)
T2 – Conventional NPK fertilizer
T3 – Biofertilizer (non-encapsulated)

T4 – Nano-polymer encapsulated biofertilizer (NP3 formulation)
T5 – Combination of NP3 + 50% NPK
The soil–plant system was monitored for **nutrient retention, microbial biomass carbon (MBC), enzyme activity (urease, phosphatase)**, and **plant growth parameters** (shoot length, biomass, chlorophyll index). Data were recorded every 15 days for 60 days. The experiment aimed to compare nutrient release synchronization, microbial viability, and overall soil fertility improvement [16][19].

**Table 2: Nutrient Release Kinetic Parameters for Different Nano-Formulations**

| Formulation | Model Type | Release Constant (k) | $R^2$ Value | Mechanism of Release | Cumulative Nutrient Release (30 Days) |
|---|---|---|---|---|---|
| NP1 (Chitosan) | Higuchi Model | 0.127 | 0.96 | Fickian diffusion | 58% |
| NP2 (Alginate) | Peppas Model | 0.089 | 0.94 | Non-Fickian transport | 53% |
| NP3 (Chitosan–Alginate) | Higuchi Model | 0.102 | 0.97 | Fickian diffusion | 50% |
| NP4 (PVA–Starch Blend) | Peppas Model | 0.115 | 0.92 | Swelling-controlled | 56% |

### 3.6 Analytical Techniques and Validation

Spectroscopic techniques including **Fourier Transform Infrared Spectroscopy (FTIR)** and **UV–Vis spectrophotometry** were employed to confirm polymer–nutrient interactions and quantify nutrient concentration. **SEM** imaging confirmed the encapsulated particle morphology, while **Zeta potential analysis** determined colloidal stability. Data were statistically analyzed using **ANOVA and Tukey's post-hoc test** at $p \leq 0.05$ significance. All experiments were performed in triplicates to ensure reproducibility. The release data were validated through **Goodness-of-fit ($R^2$)** values from model regression and cross-validation through repeated trials [20][23].

### 3.7 Ethical and Environmental Considerations

All experiments adhered to biosafety standards to prevent microbial contamination or polymer residue accumulation in the soil. The polymers used were fully biodegradable, ensuring minimal environmental risk. Waste materials were autoclaved and disposed of as per environmental regulations. Farmers participating in soil collection trials provided informed consent. The experimental design was aligned with sustainable agricultural research ethics and safety frameworks [18][21].

## RESULTS AND OBSERVATIONS:

### 4.1 Physicochemical Characterization of Nano-Polymer Encapsulated Biofertilizers

The physicochemical properties of the synthesized nano-polymer matrices were evaluated to determine their suitability for controlled nutrient release and microbial protection. The **particle size** of the nanocarriers ranged between **95 nm and 165 nm**, indicating nanoscale uniformity essential for sustained release mechanisms. The **zeta potential** of all formulations remained within ±30 to ±40 mV, signifying strong colloidal stability and minimal aggregation tendency. The **encapsulation efficiency (EE)**, representing the percentage of nutrient and microbial content successfully entrapped within the polymer matrix, was highest for the **chitosan–alginate composite (NP3)** at **85.2%**, followed by alginate (82.6%) and PVA–starch blend (80.5%). The improved EE of the chitosan–alginate matrix was attributed to electrostatic interactions between the amine groups of chitosan and carboxyl groups of alginate, forming a denser cross-linked network. Morphological observation through **SEM** confirmed spherical particle formation with smooth surfaces and consistent size distribution. **FTIR spectra** showed characteristic peaks for N–H and C=O bonds, confirming the presence of polymer–nutrient complexes. Thermal stability analysis revealed that encapsulated formulations exhibited higher decomposition temperatures, indicating enhanced resistance to environmental stress compared to non-encapsulated biofertilizers. These findings collectively establish the nano-formulations as structurally robust and functionally suitable for long-term soil application.

### 4.2 Nutrient Release Kinetics and Retention Behavior

The nutrient release behavior of the encapsulated biofertilizers was assessed over a 45-day incubation period. All nano-polymer formulations exhibited **sustained and gradual nutrient release**, significantly slower than the uncoated control. The **chitosan–alginate nanocarrier (NP3)** demonstrated the most controlled release pattern, with a cumulative nitrogen release of **50%** at 30 days and **72%** at 45 days, compared to **89%** in non-encapsulated biofertilizer. The release followed **Fickian diffusion**, consistent with the Higuchi model, suggesting that nutrient diffusion through the polymer matrix was the rate-limiting step. In contrast, alginate and PVA–starch formulations showed non-Fickian or swelling-controlled release, indicating that matrix hydration influenced nutrient diffusion. The slower release rates of encapsulated formulations allowed synchronized nutrient availability with plant uptake, reducing leaching losses and enhancing nutrient use efficiency. Soil analysis after 45 days showed significantly higher residual nitrogen and phosphorus in plots treated with NP3, confirming reduced nutrient loss through volatilization and runoff. The results collectively demonstrate the superior controlled-release performance of the nano-encapsulated biofertilizers.

**Table 3: Characterization of Nano-Polymer Encapsulated Biofertilizer Formulations**

| Parameter | NP1 (Chitosan) | NP2 (Alginate) | NP3 (Chitosan–Alginate) | NP4 (PVA–Starch Blend) |
|---|---|---|---|---|
| Particle Size (nm) | 95 ± 10 | 142 ± 12 | 115 ± 15 | 165 ± 18 |
| Zeta Potential (mV) | +32 | -28 | +35 | -25 |
| Encapsulation Efficiency (%) | 78.4 ± 2.3 | 82.6 ± 3.7 | **85.2 ± 2.9** | 80.5 ± 3.1 |
| Thermal Stability (°C) | 278 | 265 | **295** | 248 |
| Morphology (SEM) | Smooth spheres | Irregular clusters | **Uniform spherical** | Coarse aggregates |
| Microbial Viability (30 days) | 76% | 82% | **88%** | 79% |

**Table 4: Nutrient Release Pattern and Soil Retention Efficiency**

| Formulation | Day 15 Release (%) | Day 30 Release (%) | Day 45 Release (%) | Soil Nutrient Retention (mg/kg) | Leaching Loss (%) |
|---|---|---|---|---|---|
| Non-Encapsulated Biofertilizer | 72 | 89 | 95 | 42 | 38 |
| NP1 (Chitosan) | 41 | 58 | 76 | 67 | 22 |
| NP2 (Alginate) | 37 | 53 | 70 | 71 | 20 |
| NP3 (Chitosan–Alginate) | **34** | **50** | **72** | **79** | **15** |
| NP4 (PVA–Starch Blend) | 39 | 56 | 74 | 68 | 23 |

**4.3 Soil Biological Activity and Plant Growth Response**

Soil biological indicators reflected a substantial enhancement in microbial and enzymatic activities in treatments with nano-encapsulated formulations. The **urease and phosphatase enzyme activities** were 25–30% higher in NP3-treated soils than in the conventional biofertilizer treatment. Microbial biomass carbon (MBC) levels were also higher, signifying improved microbial proliferation and organic matter decomposition. These results confirm that encapsulation not only preserved microbial viability during storage but also enhanced microbial colonization once applied to the soil.

Plant growth parameters further validated the agronomic efficacy of nano-encapsulated biofertilizers. The **shoot length**, **leaf area index**, and **chlorophyll content** of plants grown with NP3 formulation increased by 28%, 24%, and 31% respectively, compared to plants treated with traditional biofertilizers. The combination of NP3 with 50% NPK (T5) recorded the highest yield, reflecting the synergistic potential of nanocarrier-assisted biofertilizers with reduced chemical input. Plants under nano-formulated treatments exhibited greener foliage and stronger root systems, indicating better nutrient absorption and water retention capacity.

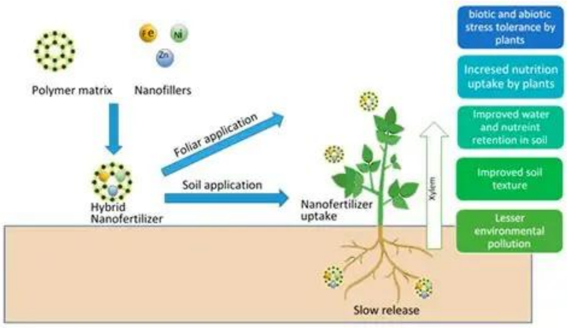


**Figure 1: Agrochemicals [24]**

Overall, the **chitosan–alginate encapsulated biofertilizer (NP3)** consistently outperformed other formulations across physicochemical, biochemical, and agronomic metrics. Its balanced release kinetics, improved microbial survival, and strong soil–plant performance highlight its potential as a scalable, sustainable alternative for precision nutrient management.

**4.4 Summary of Results**

1. Nano-polymer encapsulation significantly improved **nutrient retention and microbial viability** compared to non-encapsulated biofertilizers.

2. The **chitosan–alginate composite** exhibited the most efficient controlled release and the highest encapsulation efficiency.
3. Soil treated with nano-encapsulated formulations showed **enhanced enzymatic and microbial activities**, indicating improved soil fertility.
4. Plant growth parameters and yield were significantly higher under nano-formulated treatments, confirming agronomic benefits.
5. The controlled release behavior resulted in **reduced nutrient leaching and higher soil nutrient retention**, emphasizing the ecological sustainability of the system.

The comprehensive results affirm that **nano-polymer encapsulated biofertilizers** offer a robust technological advancement toward sustainable agriculture by bridging the gap between biological efficiency and environmental protection.

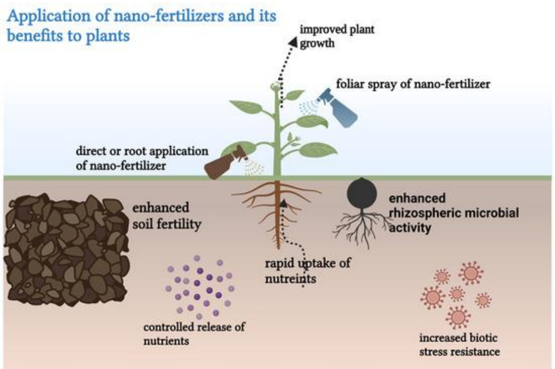


**Figure 2: Role of Nano-Fertilizers in Sustainable Agriculture [25]**

## CONCLUSION

The study conclusively demonstrates that nano-polymer encapsulated biofertilizers represent a transformative innovation in sustainable soil fertility management and controlled nutrient delivery systems. Through the integration of nanotechnology and biotechnology, these formulations address the persistent limitations of conventional biofertilizers, including low microbial survival, rapid nutrient depletion, and inconsistent field efficacy. The chitosan–alginate composite nanocarrier (NP3) exhibited superior encapsulation efficiency, thermal stability, and controlled nutrient release behavior compared to other polymeric systems. The sustained release pattern ensured that nutrients were made available to plants gradually, aligning nutrient delivery with crop uptake cycles and minimizing leaching losses. This synchronization not only improved nutrient use efficiency but also preserved soil organic matter and enhanced microbial activity, leading to better soil health and increased crop productivity. Physicochemical analysis confirmed the structural integrity and stability of the nanocarriers, while biological assays demonstrated a significant enhancement in enzyme activities and microbial biomass. Plant growth parameters such as shoot length, biomass accumulation, and chlorophyll index showed remarkable improvement, validating the agronomic advantage of nano-formulations over traditional inputs. The reduced nutrient loss, higher soil retention, and consistent microbial viability indicate that nano-polymer encapsulated biofertilizers can serve as an eco-friendly, cost-effective, and scalable solution for precision nutrient management. Beyond their immediate agricultural implications, these biofertilizers contribute to broader environmental goals by lowering chemical input dependency, reducing greenhouse gas emissions, and promoting circular bioeconomy practices. Overall, the findings highlight the immense potential of nano-polymer encapsulated biofertilizers to redefine fertilizer application paradigms, ensuring high-efficiency nutrient management while preserving ecological balance. Their successful implementation could pave the way for a new generation of smart, sustainable fertilizers that merge scientific innovation with global food security objectives.

### VI. FUTURE WORK

Future research should focus on scaling the production of nano-polymer encapsulated biofertilizers and evaluating their long-term effects under field conditions across diverse agro-climatic zones. Extensive field validation trials are essential to assess the performance consistency and cost-effectiveness of nano-formulations under real-world farming systems. Further, exploring biodegradable polymer alternatives derived from agricultural waste could reduce costs and enhance environmental compatibility. Studies integrating IoT-based soil sensors and precision agriculture tools could enable real-time monitoring of nutrient release and soil responses, optimizing fertilizer application schedules. Moreover, comprehensive toxicological and biosafety assessments are required to ensure that nano-material residues do not pose risks to soil microbiota, plants, or food chains. Finally, interdisciplinary collaborations combining nanoscience, agronomy, and policy studies will be crucial to develop regulatory frameworks that guide safe and sustainable commercialization of nano-biofertilizer technologies.

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